WOOD2WOOD

A Wood-to-Wood Cascade Upcycling Valorisation Approach

» Deliverable 5.2

Wood and glass non-destructive real time techniques analysis & optimal size definition (version 1)

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Authors	Esther Fernández
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Peer Reviewers	1. Arnaud Besserer (LERMAB) 2. Konstantinos Vasios (ICCS)

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GLOSSARY OF ACRONYMS

Acronym	Extended Definition
CDW	Construction and Demolition Waste
CQA	Critical Quality Attributes
D5.2	Deliverable 5.2
DoA	Description of the action
HSI	Hyperspectral imaging
KER	Key Exploitable Result
KPI	Key Performance Indicator
MDF	Medium-density fibreboard
NIR	Near-infrared
NIR-HSI	Near-infrared hyperspectral imaging
NIRS	Near-infrared spectroscopy
RMSECV	Root Mean Square Error of Cross Validation
RMSEP	Root Mean Square Error of Prediction
W2W	Wood-to-Wood
WP	Work Package

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EXECUTIVE SUMMARY

This deliverable (D5.2) summarizes the activities and key outcomes of Task 5.2 – "Wood and glass non-destructive real-time techniques analysis and definition of optimal size", under Work Package 5 (WP5), developed within the Wood-to-Wood Cascade Upcycling Valorisation Approach (W2W) project, funded by the Horizon Europe programme (Grant Agreement No. 101138789).

NIR-HSI (Near-Infrared Hyperspectral Imaging) is a powerful non-destructive spectroscopic technique that combines both spectral and spatial information. The optimal particle size for wood and glass samples for its evaluation and sorting with NIR-HSI has been assessed. Further optimal particle size determination will be performed with more samples of different sizes and having into account other sorting parameters.

Finally, the use of a handheld NIR resulted as a suitable method for measuring the moisture content of wood samples as well as for the identification of the type of wood (wood species) and the determination of the presence of contaminants (coatings) in wood samples.

1. INTRODUCTION

1.1. PROJECT INTRO

The W2W project proposes a comprehensive framework for multi-dimensional cascade valorisation of wood from construction and demolition and furniture waste, consisting of four core components: i) advanced separation and sorting technologies; ii) upcycling processes and technologies; iii) digital tools for improving circular flows of secondary materials; and iv) supportive framework in policy, market, and skills.

W2W will showcase efficient and sustainable value chains through three use cases focused on the production of wood-based products free from pollutants, biocomposite construction materials, biopolymers, polyols, chemical detergents, and nutrient recovery. By leveraging advanced technologies and tools, the project will identify and implement optimal cascade valorisation pathways. Taking a holistic approach, W2W aims to decrease reliance on virgin raw materials, minimize waste sent to landfills or incineration, and enable the creation of new value-added products from waste. Ultimately, the project supports the shift to a circular economy by fostering closed-loop systems where materials are continuously repurposed and reused, thereby extending their lifecycle.

1.2. PURPOSE OF THE DELIVERABLE

The purpose of this deliverable is to document the progress of the application of optical and spectroscopic characterisation techniques to determine which is the most efficient particle size of wood and glass, and the development of offline monitoring techniques to obtain real-time information.

This first version of the spectroscopic characterisation techniques serves as the foundation and stepping stone for the development of the final version (D6.2 Wood and glass non-destructive real time techniques analysis & optimal size definition (version 2)) within the next 18 months of the project.

The related key exploitable results and performance indicators associated with this deliverable and the related tasks are further detailed in the corresponding deliverables and listed below:

- **KER1:** Optimal wood size particles for cascade valorisation;
- **KPI O2.1:** To achieve a 95% accuracy of wood separation from mixed CDW sources.
- **KPI O2.2:** To adoptively sort wood based on dynamically updated classification criteria with 90% accuracy.

1.3. INTENDED AUDIENCE

The primary audience of this report is the wider public and any third parties, researchers and practitioners who are interested in optical and spectroscopic technologies for improving wood and crystal recycling. It is also addressed to the European Health and Digital Executive Agency services so as to assess the status of the W2W-task T5.2 in the context of the project's continuous reporting obligations. It also serves as the documentation of the state and intent for the development to the consortium party members so that they can coordinate their effort accordingly, where necessary.

1.4. Structure of the deliverable

The next section of the report provides the work done within Task 5.2, divided into the two main activities performed with different technologies (NIR-HSI and NIR). The first activity is focused on the determination of the most efficient particle size based on NIR-HSI analysis and the second activity is focused on the determination of moisture and type of wood by means of the Visum Palm, a handheld NIR device.

2. WOOD AND GLASS NON-DESTRUCTIVE REAL TIME TECHNIQUES ANALYSIS AND DEFINITION OF OPTIMAL SIZE

2.1. Study of the optimal particle size in wood and glass using HSI technology

Hyperspectral imaging in the near infrared range (NIR-HSI) technology was proposed as the optical and spectroscopic characterisation technique to determine the most efficient particle size of wood and glass coming from CDW.

NIR-HSI systems are imaging systems that provide a hyperspectral cube revealing the chemical composition, molecular information and distribution of a sample. A basic HSI system includes: a near infrared hyperspectral camera made of (a) a sensor, (b) a spectrometer, which separates the backscattered/transmitted light in its different wavelengths and (c) a camera lens that images a part or the full sample on the sensor; (d) a broadband illumination source (usually halogen lamps); and, when required, (e) a conveyor belt (Figure 1). A hyperspectral system provides a hypercube as output: a group of data ordered in three dimensions, two spatial (a plane XY) and one spectral (λ, wavelength). The most common acquisition mode is the line scan or push broom where a narrow spatial line of the sample surface is imaged at a time and split spectrally before reaching the two-dimensional (2D) sensor array of the camera. One dimension is used for spectral separation and the other for imaging in the line spatial direction. The second spatial dimension is obtained by moving the sample over the fixed camera.

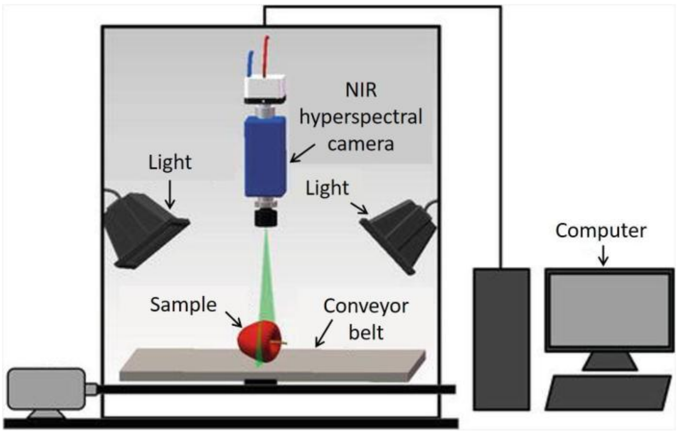

Figure 1: Basic setup of NIR-HSI principle. A NIR hyperspectral camera records line by line the diffuse reflected spectrum coming for the sample. A hypercube is then obtained. The illumination is provided by a broadband source and the conveyor enables to scan the sample below the camera. Source: DOI: 10.5772/intechopen.72250

As studied in previous researches, near infrared hyperspectral imaging (NIR-HSI) spectroscopy has been found to be a precise, rapid, low-cost and non-destructive way for wood identification (Xue *et al*., 2022).

The main objective of this first activity was to measure wood samples with IRIS' HSI system and assess which size is optimal to obtain a spectral signal of quality.

2.1.1. Materials and methods

Samples

Wood and glass samples from CDW were required. Ecomaison provided furniture waste samples to IRIS. According to them, the samples were a mixture of solid wood, particleboard, fiberboard and hardboard, whose exact composition was unknown.

IRIS was in contact with Ecomaison for receiving wood waste samples of different particle sizes (0-300 mm and 0-80 mm). Figure 2 shows the images of the samples sent by Ecomaison.

Figure 2: Ecomaison furniture waste samples (top: 0-80mm particle size; bottom: 0-300mm particle size)

The furniture waste samples were composed mainly of wood pieces. Small plastics and some glass fragments were also found. Samples were selected based on variations in particle size for both wood and glass materials, for their subsequent HSI measurements.

Moreover, IRIS sent a part of the Ecomaison samples to ICCS, as requested.

NIR-HSI spectra collecting

For this study, the IRIS technology selected was the NIR-HSI lab monitoring system, which is a robust and versatile Hyperspectral Imaging System (HSI).

IRIS was in contact with ICCS to gather information regarding their sorting line specifications (working distance, field of view, conveyor speed) for simulating the measurements with the HSI monitoring system.

The selected wood and glass samples were measured with the lab set-up HSI system at IRIS facilities, shown in Figure 3.

Figure 3: NIR-HSI lab monitoring system

Data analysis

The hyperspectral data acquired using the VISUM HSI™ software was processed and analysed using Solo+MIA™ (Eigenvector Research, Inc.), a specialized software platform for multivariate image analysis.

Background removal in HSI images is a crucial step in preprocessing, to keep pixels of interest (e.g., sample) and exclude not relevant pixels (e.g., conveyor). Subsequently, spectral data were extracted from each hyperspectral image corresponding to the different wood and glass samples. Finally, for each sample, the mean spectrum was calculated and plotted for spectral evaluation.

2.1.2. Results and discussion

Spectroscopic characterization

The generated hyperspectral images are shown together with the real images of the samples.

Figure 4 shows the images of wood samples from the 0-300mm bag. One sample is circled in blue (wood sample 1: 170x110mm), which was defined as particle board with a white coating.

Figure 4: Real image and HSI image of 0-300mm wood samples

The HSI image is shown in Figure 5, together with its NIR mean spectrum from which it can be noticed the coating contribution in the second peak of the signal.

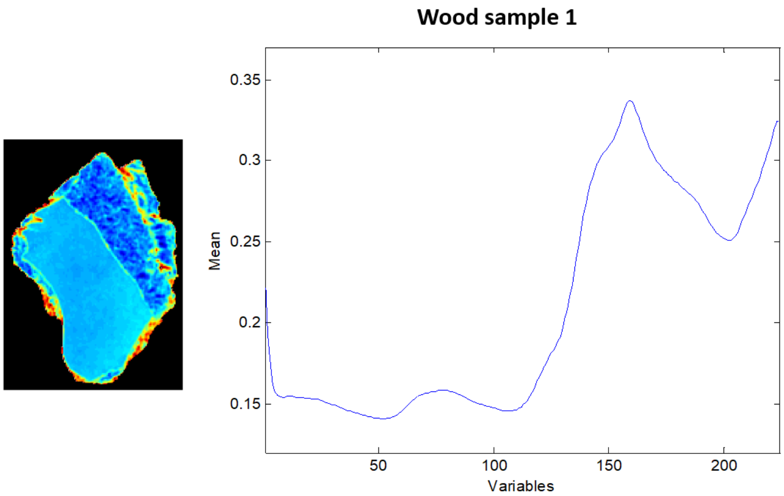

Figure 5: HSI image and NIR mean spectrum of wood sample 1

Figure 6 shows wood samples from one of the 0-80mm bags. Three samples of different particle size are circled: Sample 2 (60x60mm) in blue, sample 3 (40x50mm) in red and sample 4 (45x20mm) in green. Their respective NIR mean spectra are shown in Figure 7:

Figure 6: Real image (left) and HSI image (right) of 0-80mm wood samples (1)

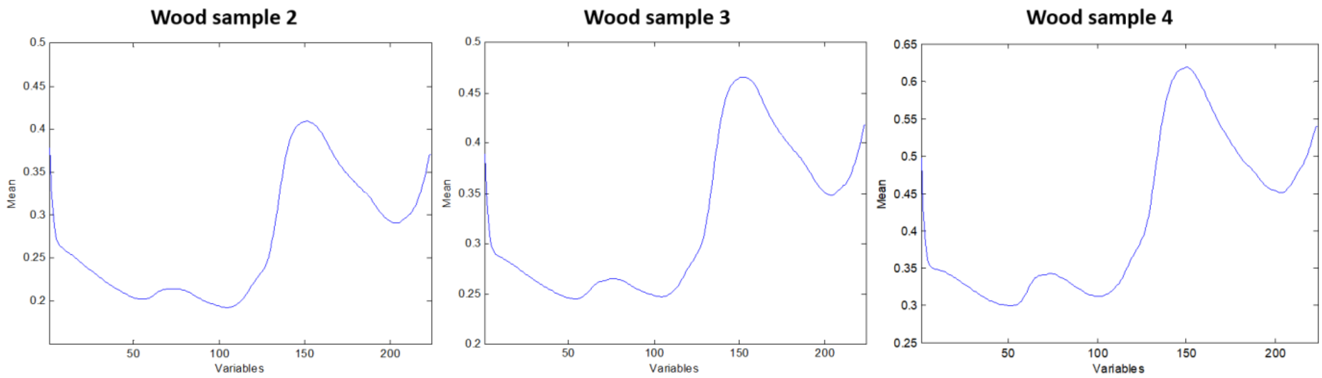

Figure 7: NIR mean spectra of wood samples 2 (left), 3 (middle) and 4 (right)

Great quality NIR spectra of those samples were achieved. Then, an inspection of smaller pieces of wood was conducted.

Figure 8 shows wood samples from the other 0-80mm bag. Two samples of similar particle size (<10x10mm) are circled in red (Sample 5) and in blue (Sample 6). Their respective NIR mean spectra are shown in Figure 9:

Figure 8: Real image (left) and HSI image (right) of 0-80mm wood samples (2)

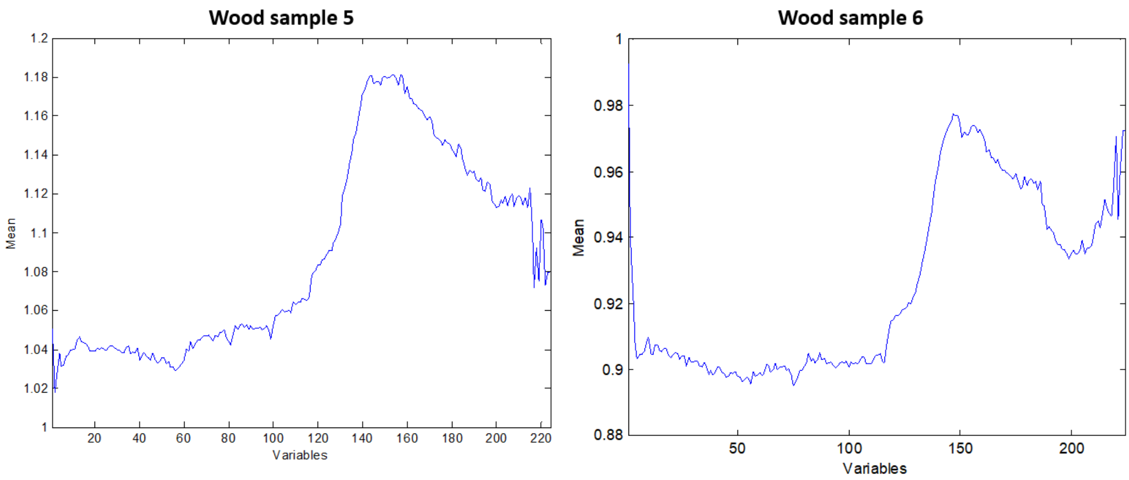

Figure 9: NIR mean spectra of wood samples 5 (left) and 6 (right)

In the last figure, a worsening in spectral quality can be clearly seen, which means that it is challenging to analyse samples with such a small particle size.

Therefore, from the samples currently available, the optimal particle size for wood samples would be within the range from 20 to 300mm. Within this particle size range, a great spectral quality of the wood samples is obtained using the HSI system. Smaller particle sizes would present a challenge for sample analysis due to the decrease in spectral quality, which could make accurate spectral interpretation difficult.

The analysis of some glass samples present in Ecomaison furniture waste samples was also conducted. Figure 10 shows the images of the glass samples. Three samples of different particle size are circled: Glass sample 1 (30x30mm) in blue, Glass sample 2 (60x40mm) in yellow and Glass sample 3 (<10x10mm) in red. Their respective NIR mean spectra are shown in Figure 11:

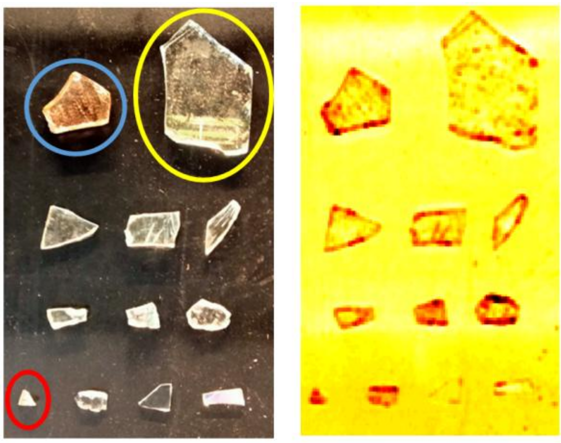

Figure 10: Real image (left) and HSI image (right) of glass samples

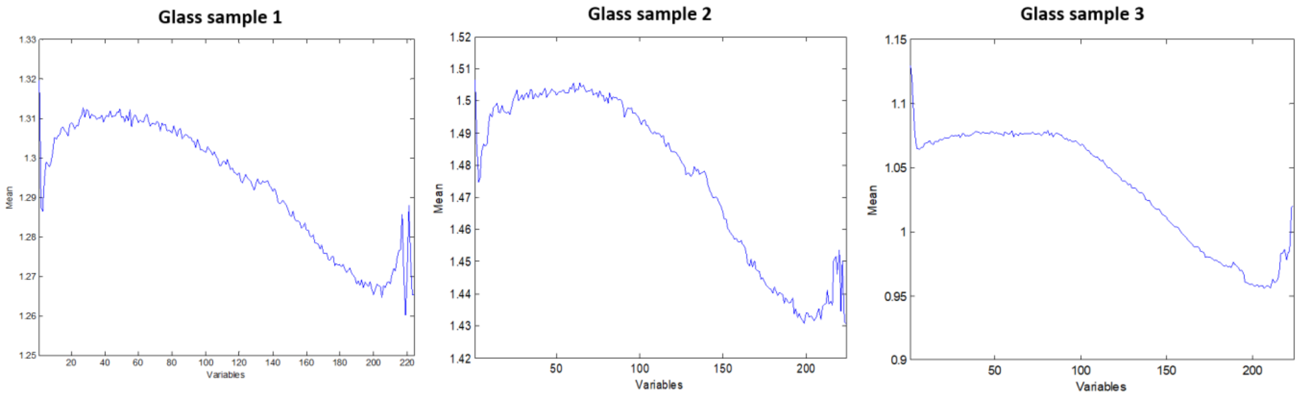

Figure 11: NIR mean spectra of glass samples 1 (left), 2 (middle) and 3 (right)

Glass, as an inorganic material, has less spectral features in the NIR region. Therefore, it can be easily differentiated from wood material facilitating its sorting.

2.2. Monitoring of Critical Quality Attributes of wood samples using an off-line handheld NIR device

The main objective for this section was to develop an offline handheld NIR monitoring system, allowing to obtain materials' information in real-time. Chemometric quantification and classification models were built, which allowed the prediction and assessment of the selected Critical Quality Attributes (CQA) of wood, such as moisture content (%) and type of wood parameters respectively.

Research studies have been performed regarding these applications during the recent years (Sundaram *et al.*, 2015; Hao, Wang and Zhang, 2021).

2.2.1. Selection of Critical Quality Attributes

As described in the DoA, and agreed with ICCS, the following key quality parameters were selected for the NIRS monitoring: moisture content (%), type of wood and the presence of coatings.

Moisture is a critical wood property due to its direct influence on material strength and density. It also significantly impacts other wood properties such as stiffness and glue curing of wood products. Therefore, monitoring moisture is essential to ensure the final quality of wood-based products (Maria et al., 2020). NIRS is widely used for moisture content determination precisely because of the detectable O–H absorption signals of water.

Another important parameter is the type of wood, which notably influences its properties, and in turn affects its end uses and how it behaves during recycling. Also, the presence of coatings on wood significantly affects its recyclability, often posing challenges in processing, safety, and material quality.

2.2.2. Materials and methods

<u>Samples</u>

For the moisture model, the samples used were the wood waste samples from Ecomaison, which are shown in Figure 1 in section 2.1.1. The sampling of the wood samples was carried out selecting the most adequate wood pieces for performing the moisture analysis and the spectral acquisition.

For the type of wood models, two different wood sample groups provided by LERMAB were used (shown in Figure 12). The first group were MDF and particle board samples with and without coatings and the second group were samples from different wood species (bamboo, oak, pinus, etc.).

Figure 12: LERMAB wood samples

<u>NIR spectra collecting</u>

For all cases, the IRIS monitoring system used to collect the NIR spectra of the wood samples was the handheld NIR device (Visum Palm).

Visum Palm™ (Figure 13) is a portable NIR analyser designed for real-time analysis of the chemical composition of a wide variety of materials and mixtures across different industries. By enabling instant analysis, it reduces laboratory time, production costs, lead times, and minimizes risks in the production chain. It is a fully autonomous analyser with an integrated computer, software, and touchscreen, eliminating the need for external devices. It allows performing all key functions directly from its interface: batch identification, analysis selection, spectra and results visualization, access to measurement histories, configuration adjustments, and user management. The analyser offers a high spectral resolution, providing precise and reliable real-time data.

Figure 13: IRIS' Visum Palm™ handheld NIR analyser

For both parameters, spectra from different points of each wood sample were acquired to capture the possible variability within the samples.

<u>Experimental work</u>

Moisture content (%)

As a first step, wood samples from the bag of particle size of 0-80 mm were selected to perform experimental tests to know the initial moisture content of the wood samples. The values were around 18-27% of moisture content. Then, with the purpose of obtaining a larger moisture range, for simulating real moisture variability contents in outdoor conditions of CDW, more wood samples were selected and some were put in the oven for different times (0 - 60min) and others were moistened.

The samples, in ceramic capsules, were left in the oven at 105ºC overnight for drying and were weighted the following day (after reaching room temperature).

<u>Data analysis</u>

The NIR data acquired using the Visum Palm™ device was processed and analysed using Solo+PLS Toolbox™ (Eigenvector Research, Inc.), a MATLAB-based software suite designed for chemometrics and multivariate data analysis.

Quantification models were used for developing prediction models for the determination of the moisture content. Classification models were built for the type of wood monitoring.

2.2.3. Results and discussion

Moisture content (%)

Quantification models were developed using the absorbance NIR spectra and the moisture content values. The quantitative accuracy of the models was evaluated using the coefficient of determination (R^2) and the root mean square error (RMSE). A total of 26 wood samples were used for developing the quantification models for moisture content (%).

Figure 14 shows the NIR spectra of the wood samples.

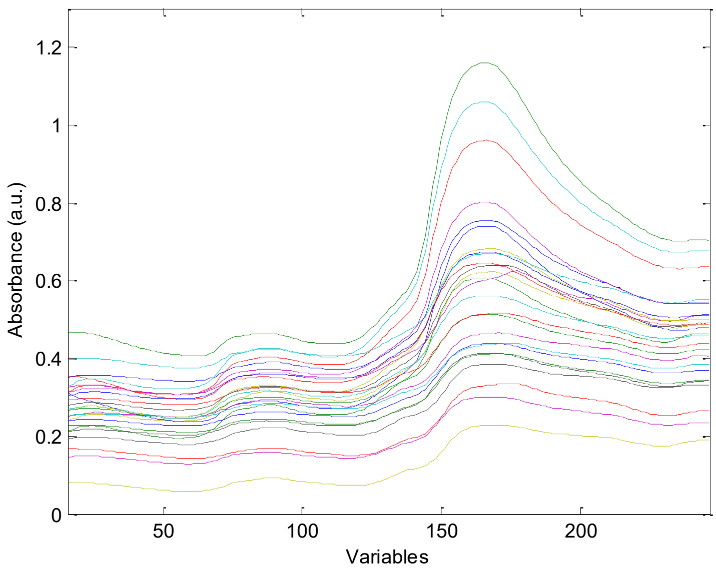

Figure 14: NIR mean spectra of the wood samples for moisture determination

The quantification model results are shown below in Figure 15. The range of the model was from 6.8 to 42.9%.

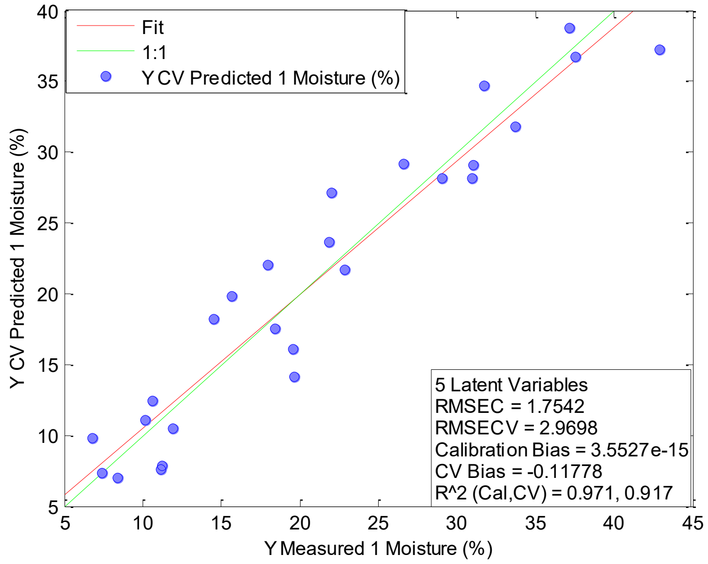

Figure 15: Predicted vs measured moisture content (%)

The developed model showed strong predictive capabilities for moisture content, with a root mean square error of cross-validation (RMSECV) of 2.97% and a coefficient of determination of cross-validation (R^2 CV) of 0.92. This indicates a significant correlation between NIR spectra and moisture data.

Furthermore, another model was built to evaluate its predictive accuracy. In this second model, the entire dataset was divided into two: a calibration or training set (approximately 80% of the samples, represented by black dots) and a validation or test set (approximately 20% of the samples, indicated by red diamonds). The purpose of this split was to assess the performance of the training model, developed using the calibration set, and its ability to predict unseen data from the same population which were not used during the calibration process (test set). The results of the second model are presented in Figure 16.

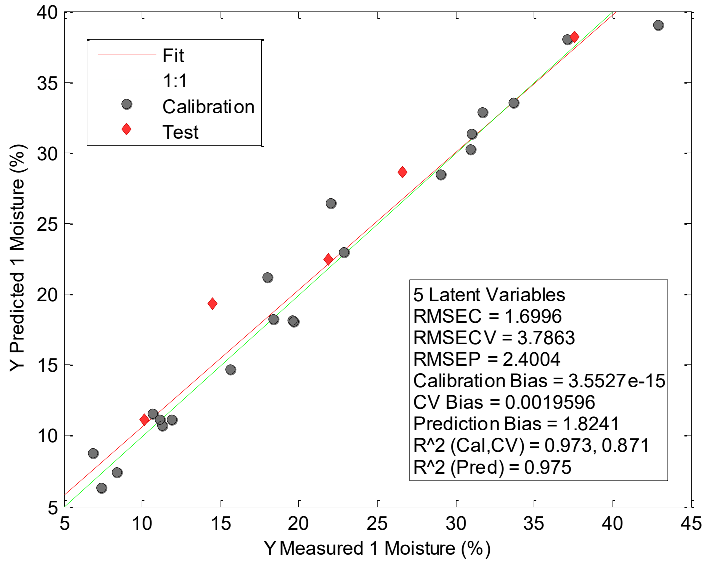

Figure 16: Predicted versus measured moisture content (%) for the second model

The results indicate a satisfactory predictive performance, with a root mean square error of prediction (RMSEP) of 2.40%.

Validation with independent samples

The first developed model was validated using the handheld NIR device on an independent set of wood samples, at IRIS facilities.

The samples used for the validation covered the range of 13.8 - 32.6% of the entire moisture model range (6.8-42.9%). Validation results are shown below in Table 1. Moisture predictions showed acceptable absolute errors ranging from 1.04 to 6.13%, with an average absolute uncertainty of 3.74%.

Table 1: Validation results of the moisture model

Sample	Experimental moisture (%)	Predicted moisture (%)	Absolute error (%)
1	32.61	29.25	3.36
2	24.65	20.14	4.51
3	14.71	20.84	6.13
4	18.04	14.59	3.46
5	13.83	14.88	1.04
6	22.12	26.12	4.00
7	24.85	28.53	3.68
Average absolute error (%)			3.74

The validation results indicate that the use of NIR spectroscopy along with chemometrics has proven to be a satisfactory method for determining the moisture percentage in wood samples.

Type of wood

An unsupervised analysis of the entire dataset was conducted (classes: coated MDF, uncoated MDF, coated particleboard, uncoated particleboard and solid wood). A lot of spectral variability was found within the solid wood class due to the presence of different wood species. Therefore, it was decided to build two separate classification models:

1. Determination of the presence of a coating (as contaminant).

   The NIR mean spectra of the different wood classes is shown in Figure 17:

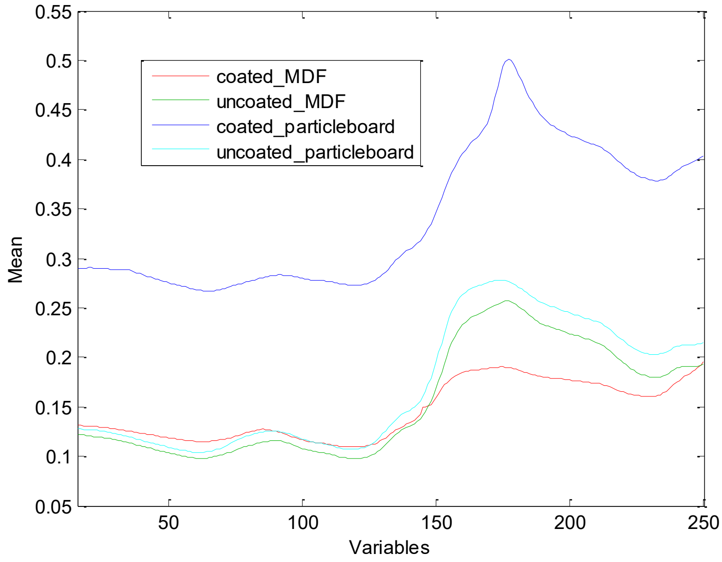

Figure 17: NIR mean spectra of 4 different wood classes

Classification models were built. The scores results of the uncoated vs coated classes are shown in Figure 18:

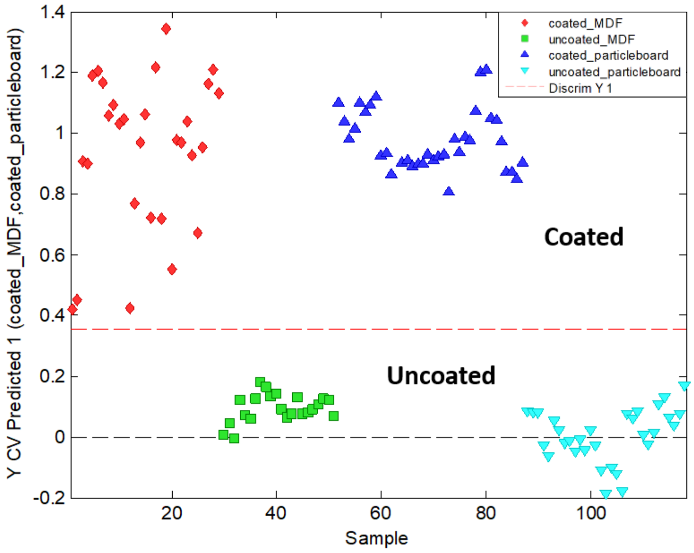

Figure 18: Scores of CV results for the coated vs uncoated classification model

High variability was found within the coated MDF class, probably due to the presence of different types of coatings (as can be seen in Figure 18 with the dispersion of the red points).

2. Identification of wood species.

After the analysis of the spectra of all the samples, 6 classes (bamboo, fir, oak, pinus, spruce and tropical wood) were selected to develop the classification model. Figure 19 shows the NIR mean absorbance spectra of the abovementioned wood classes:

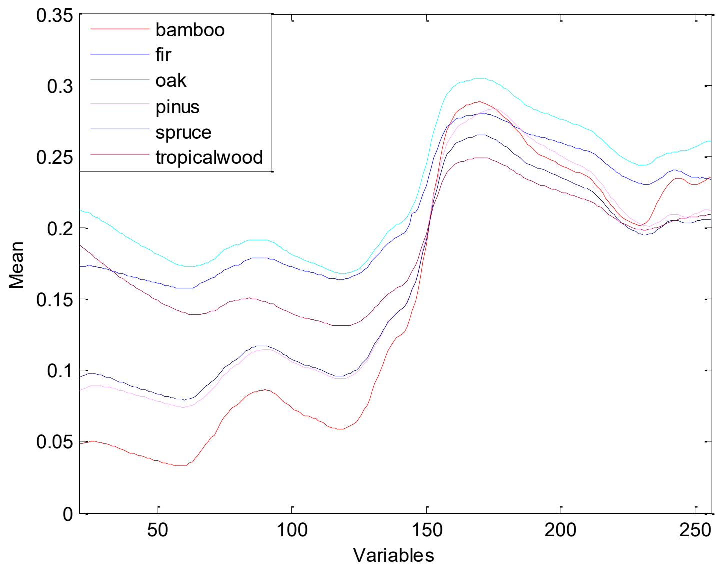

Figure 19: NIR mean spectra of solid wood classes

Three different classification models were built. The first one divided the samples into two main groups: wood from coniferous trees (fir, pinus and spruce) and wood from non-coniferous trees (bamboo, oak and tropical wood). The scores results of the first classification model are shown in Figure 20:

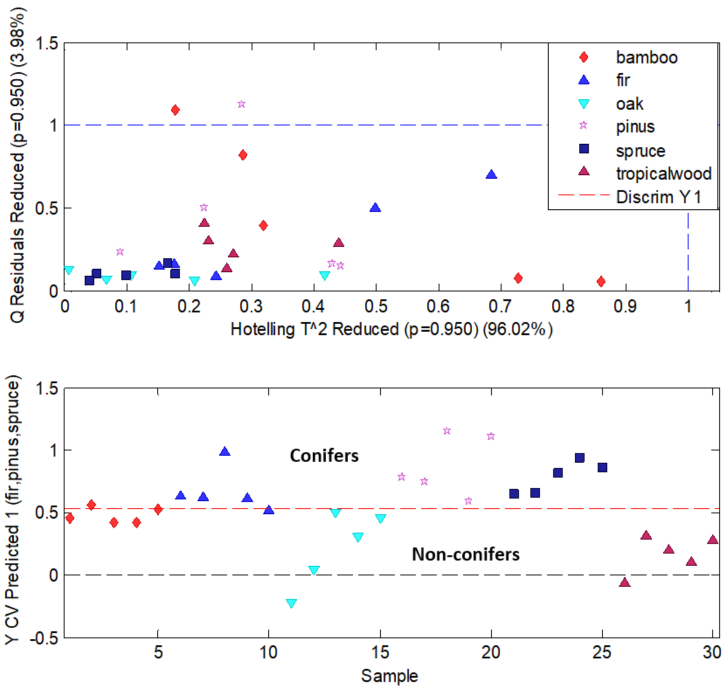

Figure 20: Scores of CV results for the conifers vs non-conifers classification model

Then, from each group two separate classification models were developed to classify each wood species. The scores results of the second and third classification model are shown in Figure 21 and 22, respectively:

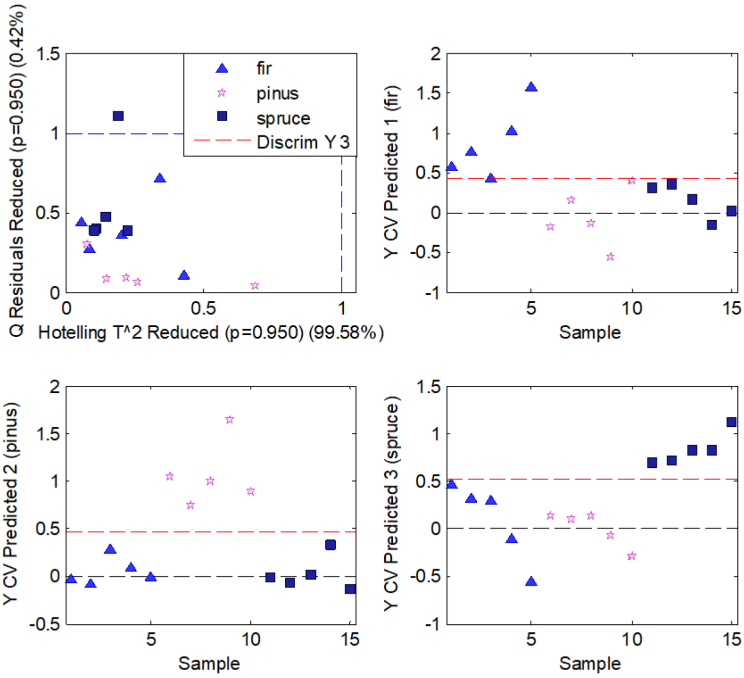

Figure 21: Scores of CV results for the conifers classification model

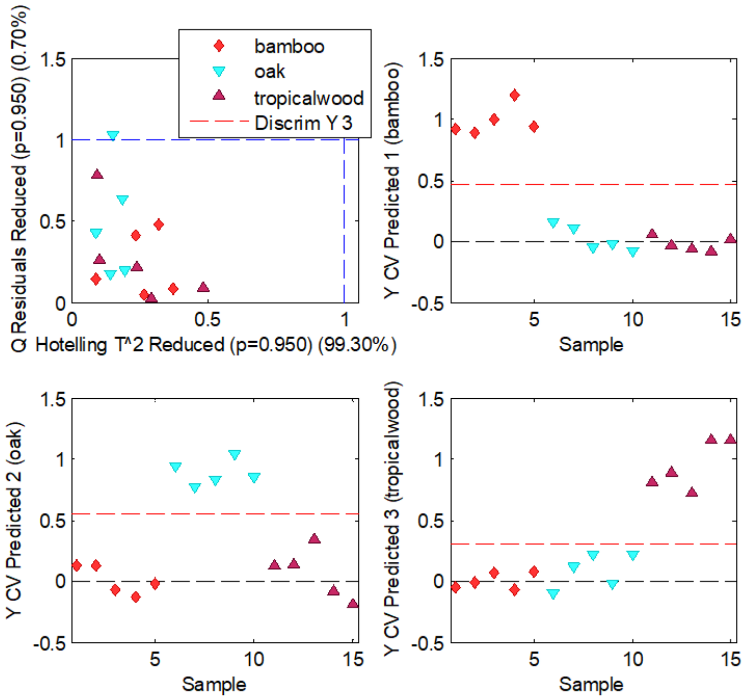

Figure 22: Scores of CV results for the non-conifers classification model

Moreover, the classification models were validated using an unknown sample (without label from LERMAB). In the first model the sample was predicted in the class of the non-conifers wood, which is shown in Figure 23.

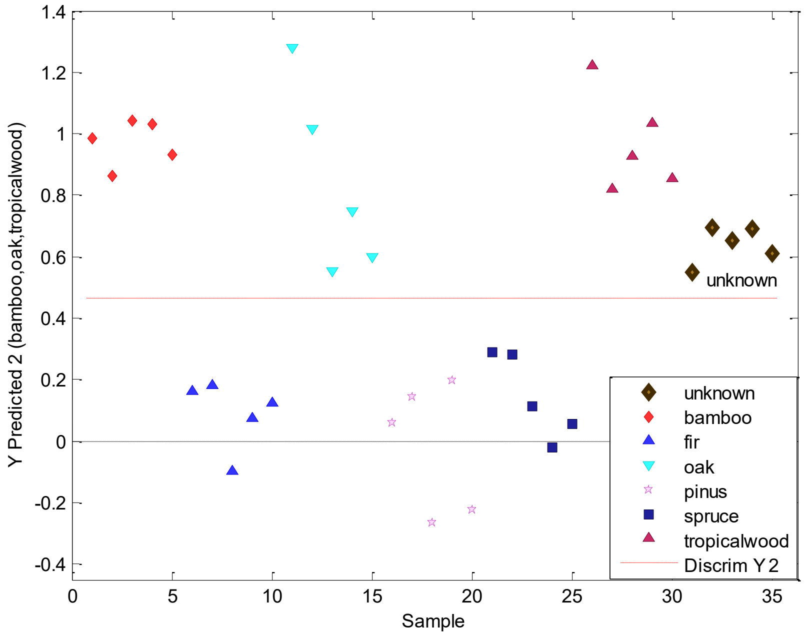

Figure 23 : Prediction results of the unknown wood sample in the first classification model

Then, this sample was tested in the non-conifers classification model, yielding oak as the predicted class. It should be noted that it cannot be stated categorically that this unknown sample belongs to the class assigned by the model, due to the limited number of samples and classes that the model has been trained with. This is a found limitation that could be addressed in the next Task (T6.2) by incorporating a larger number and greater variability of samples, which would enhance the robustness of the models.

3. CONCLUSION

NIR-HSI (Near-Infrared Hyperspectral Imaging) is a powerful non-destructive spectroscopic technique that combines both spectral and spatial information.

The optimal particle size for NIR-HSI evaluation and sorting of wood samples would be within the range from 20 to 300mm, and not less than 10mm. In the case of glass samples, samples with sizes from 10x10mm can be properly identified. Further optimal particle size determination will be performed with more samples of different sizes and taking into account other sorting parameters such as the capability of the sorting system to reject the sample among others.

NIR spectroscopy using the Visum Palm™ handheld NIR analyser has proven to be a suitable method for both monitoring activities. With regards to the moisture content parameter, successful results were obtained with great predictive accuracy of the quantification model (correlation (R^2) of 0.973 and RMSEP of 2.40%). For the type of wood classification, satisfactory outcomes were accomplished with a 100% of successful identification of contaminated (coated) and uncoated wood samples and of the identification of wood species.

As a conclusion, the results demonstrate that NIR spectroscopy can offer highly valuable insights for monitoring moisture content and type of wood (presence of coating as contaminant and species identification) in wood samples. These activities provide real-time information which could significantly help in the waste streams management process.

The work performed in the Task 5.2 within the WP5 and reported in this Deliverable D5.2 (version 1) will be continued and scaled-up in Task 6.2 (WP6) and reported in the final version D6.2 (version 2).

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